CABLE SBIR Subtopic a. TECHNOLOGY TRANSFER OPPORTUNITY: Metal-carbon composition and composites manufacturing

of Topic 20 of DOE SBIR/STTR Phase I/ Release 2 JOINT TOPIC: CABLE MATERIALS AND APPLICATIONS

CABLE TOPIC INFORMATION APPLICABLE TO ALL CABLE SUBTOPICS (20a-h)

Maximum Phase I Award Amount: $200,000	Maximum Phase II Award Amount: $1,100,000
Accepting SBIR Phase I Applications: YES	Accepting STTR Phase I Applications: YES

The objectives of the Conductivity-enhanced materials for Affordable, Breakthrough Leapfrog Electric and Thermal Applications (CABLE): Materials and Applications topic are 1) to transfer technology for the fabrication of breakthrough CABLE enhanced conductivity materials and 2) to support leapfrog applications in the design and use of enhanced conductivity materials that will make the performance improvements and energy savings of these applications more affordable.

This joint topic is a collaboration among the following EERE Technology Offices: Advanced Manufacturing, Building Technologies, Geothermal Energy Technologies, Solar Energy Technologies, and Vehicle Technologies as well as the DOE Office of Electricity [1]. Please refer to each office's specific topics for more information about each office.

The use of electricity in the U.S. and worldwide is currently undergoing multiple paradigms shifts in how electricity is generated, delivered, and consumed [2, 3]. There is a critical need for advances in the materials and means by which electricity is translated from generation to use. The demand for CABLE materials and applications are increasing as sectors become increasingly electrified [4]. In addition, there is an urgent need to upgrade electric systems for greater grid reliability because of increasing renewables and distributed energy resources (DERs), and resilience from evolving threats such as cyber-attacks and extreme weather offers a once in a lifetime window of opportunity to upgrade the fundamental materials and applications that support it.

While DOE has funded research on high conductivity materials before, the comprehensive CABLE approach mandates that a breakthrough in electrical or thermal conductivity be balanced with maintenance of other properties needed for applications above a certain minimum value, with minimum standards described in the application specific subtopics below. Furthermore, the CABLE material and its applications must be sufficiently broad and affordable that it enables leapfrogging international competitors and fostering a host of new manufacturing industries to make higher performing materials and the products—everything from transmission and electric vehicle (EV) cables to solar cells—enabled by them.

This topic supports the objectives of the Energy Storage Grand Challenge, Grid Modernization Initiative, and DOE's support for Advanced Manufacturing as part of its support for to advance the Industries of the Future. Advancements in CABLE materials also support the objectives of the Critical Minerals Initiative.

This topic comprises two distinct, complementary focuses critical to achieve the CABLE objectives.

CABLE materials innovations are the subject of subtopic a) where enhancing conductivity—a "breakthrough, leapfrog" improvement compared to state of the art—must be balanced by meeting all applicable minimum standards for future commercialization of applications (including subtopics b-h). Note that the nano-carbon infusion approach of subtopic a is only one of many promising approaches (many of which also involve the use of critical materials) to make CABLE materials [5, 6, 7, 8,9]. Proposals for research on approaches other than that in subtopic a) are not, however, being sought under this Topic at this time.

CABLE applications (subtopics b-h) should include enhanced conductivity materials (from subtopic a) or other new materials [5 ,6, 7, 8] that meet or exceed metrics specified for each application and to the current state of the art. Even though these applications appear prosaic where substantial R&D effort has been made previously, the CABLE applications listed below, all have the potential to be Breakthrough and Leapfrog because for the first time the research includes re-designing for enhanced conductivity material—something never done before—and exploring the manufacturing and regulatory barriers involved in the use of such materials in pervasive applications.

Enhanced conductivity materials NOT of interest (or applications that rely on them) include:
- Standard superconducting materials;
- High-temperature superconducting materials; and
- Primarily magnetic materials;
- Proposals that focus on these materials will be deemed nonresponsive to this topic.

All proposals to this topic must:
- Propose a tightly structured program which includes clear, CABLE-relevant technical milestones/ timeline that demonstrate clear progress, are aggressive but achievable, and are quantitative;
- Provide evidence that the proposer has relevant CABLE and/or OE/EERE experience and capability;
- Clearly define metrics and expected deliverables;
- Explain applications of project output and potential for future commercialization;
- Include projections for cost and/or performance improvements that are tied to a clearly defined baseline and/or state of the art products or practices;
- Explicitly and thoroughly differentiate the proposed innovation with respect to existing commercially available products or solutions;
- Include an energy savings impact and impact grid as well as a preliminary cost analysis;
- Report all relevant performance metrics; and
- Justify all performance claims with theoretical predictions and/or relevant experimental data.

The Phase I application should detail material, design and/or bench scale systems that are scalable to a subsequent Phase II prototype development. Applications must be responsive to the following subtopics. Applications outside of these subtopic areas will not be considered.

CABLE Subtopic a: TECHNOLOGY TRANSFER OPPORTUNITY: Metal-carbon composition and composites manufacturing

This subtopic is the only one in this topic to focus on the conductivity enhanced materials part of the CABLE effort. This subtopic seeks proposals to commercialize the innovation in CABLE materials manufacturing presented in the May 2020 patent and related patent applications from Argonne National Laboratory listed below.

The patent solves one of the technical problems for manufacturing high purity, oxygen-free metal-carbon composites with an electric current. These carbon-infused "covetic" metal alloys might lead to significant energy savings and performance improvements in various applications (e.g., high-voltage electrical transmission, electrical motors and generators, advanced heat exchangers, electrodes for fuel cells, batteries, supercapacitors, and for thermal management in micro- and power electronics). This fabrication method allows precise control of the composition of the covetic material to be produced. The method described herein also can be applied to produce multi-element-carbon composites within a metal or alloy matrix, including high melting temperature materials such as ceramic particles or prefabricated nano- or micro-structures, such as carbon nanotubes or graphene compounds. The covetic reaction between metal and carbon takes place under the influence of flowing electrons through the melted metal-carbon precursor. This process posited to create strong bonding between nanocarbon structure and the metal elements in the melt.

The 2019 patent application is for the initial version of the method to make covetic metal-nanostructured carbon composites or compositions. The method comprises the introduction of carbon into a molten metal in a heated reactor under low oxygen partial pressure, and the passing of an electric current through the molten metal. After heating the covetic material is recovered from the reactor.

The 2020 patent application is for a method for preparing a covetic, nanocarbon-infused, metal composite material by heating a stirring molten mixture of a conducting metal (e.g., Cu, Al, Ag, Au, Fe, Ni, Pt, Sn, Pb, Zn, Si) and carbon (e.g., graphite) at a temperature sufficient to maintain the mixture in the molten state in a reactor vessel, while passing an electric current through the molten mixture via at least two spaced electrodes submerged or partially submerged in the molten metal. Each of the electrodes has an electrical conductivity that is at least about 50 percent of the electrical conductivity of the molten mixture at the temperature of the molten mixture. Preferably, the conductivity of the electrodes is equal to or greater than the conductivity of the molten mixture.

Please refer to Topic 9 (AMO) for other opportunities related to Advanced Manufacturing technologies.

Patent Status:

- U.S. Patent No. 10,662,509 B2, "Metal-carbon composition and composite manufacturing method" Issued May 26, 2020.

- U.S. Patent Application No. US 2019/0381563 A1 "Method for making metal-nanostructured carbon composite

- U.S. Patent Application No. US 2020/0176573 A1 "Electrodes for making nanocarbon - infused metals and alloys"

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Q&A (Subtopic a)

Q: What is the desired TRL at the end of Phase I?
A: We are looking for a proof-of-concept from Phase I, in the range of TRL 2-4.
Q: What is the desired TRL at the end of Phase II?

A: Phase II is dependent on the progress made in Phase 1, but we would preliminarily be seeking TRL 3-6.

Q: Can any conducting metal be used with this carbon-infusion process? I don't see Magnesium (Mg) on the list of materials in the patent.

A: While Mg is not on the list in the patent (e.g., Cu, Al, Ag, Au, Fe, Ni, Pt), the language preceding the list is "including" which in legal parlance always implies "but not limited to." Thus, any metal that is conductive can be used with the nano-carbon infusion (covetic) process.

References (Subtopic a)

1. Balachandran, B., "High-Performance Electrical and Thermal Conductors" U.S. DOE Advanced Manufacturing Office Virtual Program Peer Review Meeting, June 2-3, 2020, https://www.energy.gov/sites/prod/files/2019/07/f65/Projects19%20-%20High%20Performance%20Electrical%20and%20Thermal%20Conductors_ANL.pdf

General References

1. For more information on the DOE offices that comprise CABLE see the following websites: Office of Electricity (OE) (https://www.energy.gov/oe/office-electricity); and those for seven Offices within DOE's Office of Efficiency and Renewable Energy (EERE): Advanced Manufacturing Office (AMO) (http://energy.gov/eere/amo), Building Technologies Office (BTO) (http://energy.gov/eere/buildings), Solar Energy Technologies Office (https://www.energy.gov/eere/solar/solar-energy-technologies-office), the Geothermal Technologies Office (GTO) (https://www.energy.gov/eere/geothermal), the Vehicle Technologies Office (VTO) (https://www.energy.gov/eere/vehicles/vehicle-technologies-office); the Wind Energy Technologies Office Wind Energy Technologies Office (WETO) (https://energy.gov/eere/wind) and the Water Power Technologies Office (WPTO) (http://energy.gov/eere/water/water-power-program).

2. U.S. Energy Information Administration (EIA). "Annual Energy Review (AER) 2020." https://www.eia.gov/totalenergy/data/annual/

3. U.S. Energy Information Administration (EIA). "U.S. EIA Annual Energy Outlook (AEO) 2020." https://www.eia.gov/outlooks/aeo/

4. Roberts, D. "The Key to Tackling Climate Change: Electrify Everything." Vox, Oct 27, 2017, https://www.vox.com/2016/9/19/12938086/electrify-everything

5. Cao, M., Xiong, D.B., Yang, L., Li, S., Xie, Y., Guo, Q., Li, Z., Adams, H., Gu, J., Fan, T., Zhang, X., and Zhang, D. "Ultrahigh Electrical Conductivity of Graphene Embedded in Metals." *Adv. Funct. Mater*. 2019, 29, 1806792 DOI: 10.1002/adfm.201806792, https://www.researchgate.net/publication/331403006_Ultrahigh_Electrical_Conductivity_of_Graphene_Embedded_in_Metals#:~:text=Ultrahigh%20electrical%20conductivity%20%E2%89%883000%20times%20higher%20than%20that,electrical%20conductivity%20significantly%20higher%20than%20that%20of%20Ag

6. Kappagantula, K., et al. "Better Copper Means Higher Efficiency Electric Motors." PNNL, October 2020, https://www.pnnl.gov/news-media/better-copper-means-higher-efficiency-electric-motors

7. Subramanian C., et al. “One-hundred-fold increase in current carrying capacity in a carbon nanotube–copper composite.” Nat. Comm. 4 2202 [DOI: 10.1038/ncomms3202 |www.nature.com/naturecommunications]. Jul 23, 2013, https://www.ncbi.nlm.nih.gov/pmc/articles/PMC3759037/

8. Bystricky P., Lashmore D., Kalus-Bystricky I. “Metal matrix composite comprising nanotubes and methods of producing same” IPN: WO2018/126191 A1 p.1. Jul 5, 2018. https://patentscope.wipo.int/search/en/detail.jsf?docId=WO2018126191

9. Tehrani, Mehran “Advanced Electrical Conductors: An Overview and Prospects of Metal Nanocomposite and Nanocarbon Based Conductors”, https://arxiv.org/submit/3454010/view